

Gas flow in close binary star systems

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Summary

We first present a summary of our numerical work on accretion discs in close binary systems. Our recent studies on numerical simulations of the surface flow on the mass-losing star in a close binary star is then reviewed.

1 Accretion discs

An accretion disc around a compact star in a close binary star system is an ubiquitous and essential object. Accretion discs play, for example, important roles in cataclysmic variables, nova and X-ray sources. The standard theory to explain the physics in accretion discs is the α -disc model proposed by Shakura and Sunyaev (1973). In this theory, the accretion disc is in some kind of turbulent state, in which turbulent viscosity is parameterized by a phenomenological parameter α .

However, the α -disc model is rather crude approximation to an accretion disc in a close binary system: tidal effects due to the companion star are, for example, not taken into account. To better take these effects into account, one has to rely on numerical simulations.

1.1 Numerical simulations of gas flow in a close binary system

A pioneering numerical study of accretion discs in close binary systems was started by Prendergast (1960). At that time both computers and computational fluid dynamics were not well developed, so his work was only a preliminary one. It should be noted that Prendergast also started a pioneering work on barred galaxies at that time.

Prendergast & Taam (1974) made a first reliable calculation of gas flow in a close binary system using the beam scheme developed by Prendergast. The beam scheme can be considered as a forerunner of the lattice Boltzmann

scheme. In order to solve for the fluid flow, the scheme uses the Boltzmann equation rather than the Euler equation as a basic equation. The velocity distribution function has values only at fixed points in velocity space. The original scheme had the drawback of too much artificial viscosity.

At that time, Sorensen Matsuda & Sakurai (1974, 1975) were working on a numerical study of gas flow in a close binary system, and they were surprised to find the paper by Prendergast and Taam. However, since the size of their mass-accreting star was very large, their model corresponded to the maybe less interesting Algol-type binaries rather than to cataclysmic variables or X-ray stars.

Sorensen et al. (1974, 1976) adopted a much smaller size of the mass-accreting star to simulate a compact star, although the size was still much larger than that of a realistic compact star, i.e. a white dwarf, a neutron star or a black hole. If the numerical size of the compact star is smaller than the so-called circularization radius, an accretion disc may be formed.

Sorensen et al. used the Fluid in Cell Method (FLIC) with first order accuracy, and computed the flow only in the orbital plane, using a Cartesian grid. Figure 1 shows the density distribution and velocity vectors of a Roche-lobe over-flow in a semi-detached binary system with a mass ratio of one. Gas flows out from a mass-losing star (left) through the L1 point towards a mass-accreting compact star (right). The L1 stream, similar to an elephant trunk is visible but the accretion disc is not well resolved.

Lin & Pringle (1976) investigated a similar problem using the sticky particle method, which utilizes both particles and cells. Particles entering a cell are assumed to collide, and velocities of particles after the collision are calculated assuming the conservation of momentum and angular momentum. This method may be thought as a forerunner of SPH scheme, which is a particle scheme frequently used in the astrophysics community, but it would be more appropriate to consider it as a forerunner of the Direct Simulation Monte Carlo method (DSMC) developed later by Bird (see Bird, 1994). In DSMC, the number of particles in a cell is generally much larger, typically 10-100, and collision pairs are selected randomly based on collision probability. The present authors investigated applications of DSMC to astrophysics.

1.2 Modern calculation of accretion flow

Sawada et al. (1986, 1987) investigated again two-dimensional calculations of accretion discs using the Osher upwind scheme and Fujitsu VP200/400 vector supercomputers. Figure 2 shows the density distribution in the orbital plane in a semi-detached binary system with unit mass ratio. They first made their calculations using a first-order scheme. When they switched to a second-order scheme, they discovered a pair of spiral shaped shock waves, as seen in the figure. It is very suggestive that using higher order scheme reveals a new feature which could not be seen in a scheme with lower accuracy.

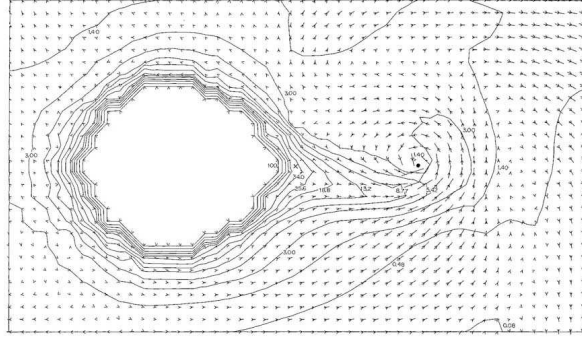


Fig. 3. Density contours and velocity vectors for $\eta=1$, $TM_0=0.745$ and $RG_0=0.05$ [details in Section 3].

Figure 1 Two-dimensional hydrodynamic simulation of accretion disc using FLIC method: Density distribution and velocity vectors on the rotational plane are shown. The left oval shape is a mass-losing companion star, while the dot at the right shows the position of a mass-accreting compact object. Gas from the companion star flows through the L1 point towards the compact star due to the gravitational attraction to form a so-called elephant trunk (after Sorensen et al. 1975).

Spiral shocks in an accretion disc may represent an interesting possibility to solve a long-standing mystery in the theory of accretion discs, i.e. the problem of angular momentum transfer. In order for accretion to occur, the gas in the accretion disc has to lose its angular momentum. In conventional standard disc model, the disc is supposed to be in a turbulent state and the transfer of angular momentum is supposed to occur through the turbulent viscosity. However, in spite of many efforts to show the disc to be unstable, there has been no success.

In the spiral shock model, gas loses angular momentum at the shocks. Nevertheless, the spiral shock model had not attracted much attention from researchers, and there was even an opinion that spiral shocks did not exist in three-dimensional calculations. Sawada & Matsuda (1992) performed the first three-dimensional hydrodynamic calculation and obtained spiral shocks. Figure 3 shows our recent calculation by Fujiwara et al. (2001). The figure shows an iso-density surface of an accretion disc around a compact object. Flow-lines on the iso-density surface and on the orbital plane are visualized by the LIC method.

1.3 Discovery of spiral shocks by observation

As was pointed out earlier, the spiral shock model may solve the long-standing angular momentum problem. Even if not so, if spiral shocks are present, they must have some observational implications. In 1997, they were apparently

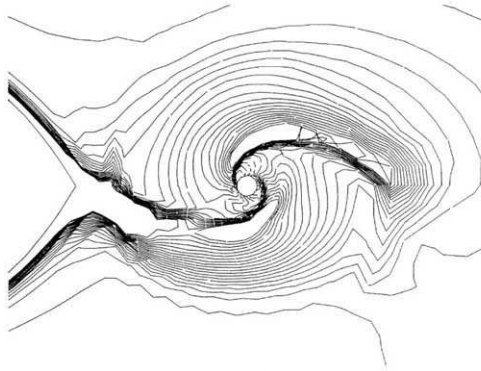


Figure 2 Calculation based on the second-order Osher scheme: Density distribution on the rotational plane is shown. A circle at the center represents a mass-accreting compact object. Gas from the mass-losing companion (at left) flows through the L1 point and forms an accretion disc. A pair of spiral shock in the accretion disc can be seen (after Sawada et al. 1986, 1987).

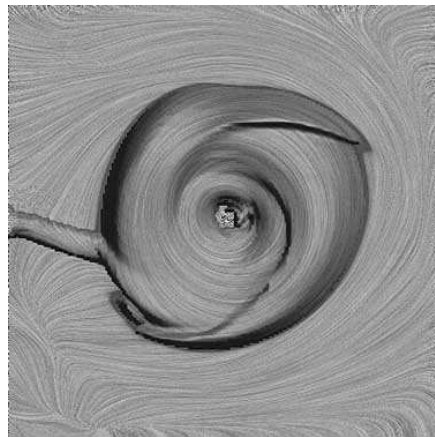


Figure 3 Recent three-dimensional calculation: Iso-density surface and flow-lines on the surface/rotational-plane are shown. Three-dimensional structure of spiral shocks is evident. It is remarkable that the flow from the L1 point penetrates into the disc (after Matsuda et al. 2000).

detected by Steeghs, Harlaftis & Horne (1997) in the cataclysmic variable, IP Pegasi, using the Doppler tomography technique.

Tomography is a technique used, for example, to visualize a cross section of the human body by measuring the absorption of irradiated X-rays. In Doppler tomography, emission lines of hydrogen or helium emitted from hot gas circulating around a compact star are observed and analyzed to give a Doppler map. In X-ray tomography, it is the illuminator that rotates about a human, but in the case of Doppler tomography, use is made of the rotation of the binary system. From temporal variation of the spectrum, one can construct a Doppler map, which is a distribution of emission in the velocity space. From a Doppler map only, it is however not possible to construct uniquely the density distribution in the configuration space. Nevertheless, we may draw useful information from Doppler maps. For example, if spiral structure of hot region emitting spectrum lines exists, it is reflected as a spiral structure in the Doppler map. Steeghs et al. found such a structure.

The ring-like structure observed in a Doppler map represents an accretion disc. If the disc is axi-symmetric around a compact star, as is assumed in the standard disc model, the emission structure should be also axi-symmetric. However, the emission structure shows a spiral feature.

Interestingly, the surface of the mass-losing companion star is also bright. This is because the surface of the companion is irradiated by a radiation from the hot central part of the accretion disc. Moreover this bright region on the companion star is shifted slightly from a symmetry axis. It may be due to a current on the surface of the companion star.

2 Flow on a companion surface

2.1 Flow pattern

So far we discussed the flow in an accretion disc around a compact star, because there have been lots of works both theoretical and observational. On the other hand the companion star donating gas to the accretion disc has not attracted much attention, because it is difficult to observe the flow on its surface. The only exception was the semi-analytic work by Lubow and Shu (1975), who predicted the existence of an astrophysical wind on the companion surface. But quite recently, surface mapping of the companion in cataclysmic variables became possible (see e.g. Dhillon & Watson 2000 for the review).

Oka et al. (2002) performed a three-dimensional simulation of the surface flow on the companion and discovered three kinds of eddies associated with a high/low pressure on the companion surface: the H-, L1, and L2-eddies. The notations H, L1 and L2 denote the high pressure around the pole, the low pressure around the L1 point and the low pressure at the opposite side to the L1 point, respectively.

Figure 4a shows streamlines on the surface of the companion star in a semi-detached binary system with mass ratio 2; the companion is assumed to

be two times heavier than the mass-accreting compact star. This mass ratio is taken to model a supersoft X-ray source. Figure 4b shows the accretion disc for the mass ratio of 2. Note that Figs. 4a and 4b are not the result of one calculation. In Fig. 4a the ratio of specific heats, γ , is assumed to be $5/3$, i.e. an adiabatic gas, while in Fig. 4b, $\gamma = 1.01$ is adopted to obtain an accretion disc. In order for an accretion disc to be formed, some kind of cooling is necessary, and we mimic the cooling by lowering γ .

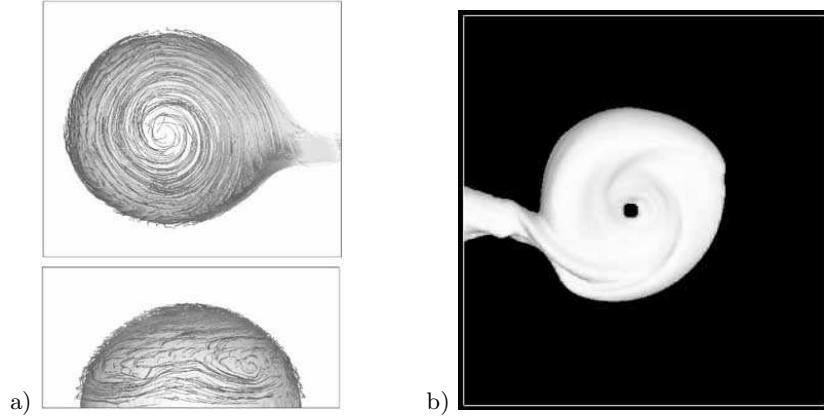


Figure 4 a) Iso-density surface of the companion star and the streamlines, viewed from the north (top) and those viewed from the negative x direction (bottom). The mass ratio is 2 and the specific heat ratio is $\gamma = 5/3$. b) Iso-density surface of the accretion disc. The specific heat ratio of $\gamma = 1.01$ is adopted.

These eddies are nothing but the manifestation of the astrophysical wind predicted by Lubow and Shu (1975). In a rotating fluid, the pressure gradient force balances the Coriolis force, and therefore the wind blows along isobaric lines. Since gas is withdrawn from the L1 point, a low pressure is inevitably formed near the L1 point. Gas near the equator feels less Coriolis force and easily flows towards the L1 point, and thus the equatorial region becomes a low pressure region. Because of this, a high pressure is formed near the pole regions. The mechanism of the formation of the L2 eddy is much more complicated.

2.2 Doppler map

Based on the above result, we can construct a Doppler map of the surface flow. This is not an easy task, because the emission lines are emitted from the photosphere of regions of hot temperature. We need to know the temperature distribution on the photosphere and have to calculate ionization states

of either hydrogen or helium on it. Temperature of the photosphere of the companion star is very much affected by the irradiation from the central region of the accretion disc and the surface of the compact star. Since, in the present calculation, we do not take irradiation effect into account, we cannot construct real observable Doppler map.

We use the following convention. As a candidate of the photosphere, we take an iso-density surface, and plot the horizontal velocity components, V_x and V_y , of the gas on the $V_x - V_y$ plane, i.e. Doppler map.

Figure 5 shows the so constructed Doppler map. There are a few characteristics to be mentioned. The dark area in and around the companion star is due to the gas on the surface of the companion. The fact that it is not restricted within the oval shape is reminiscent from the surface flow. If there is no flow, the dark region should be within the oval shape. Note that all these dark area is not observable, since we do not plot the spectral line intensity in this figure. We may argue that the present model Doppler map may be able to explain some observational feature in some of supersoft X-ray sources. The ring-like structure represents the accretion disc. This shape agrees well with observations.

The present model Doppler map is of course a very crude one. We have to perform simulations including radiative transfer to construct more realistic Doppler map. This is our future task.

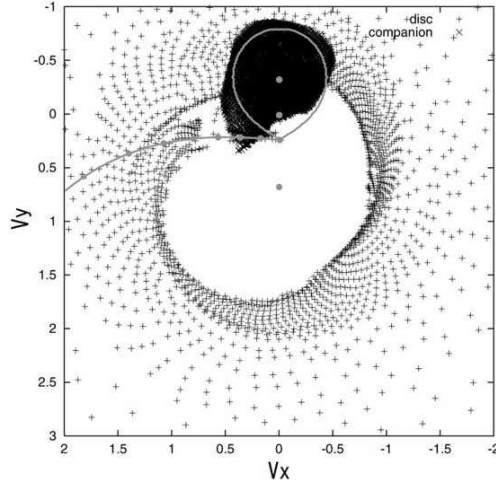


Figure 5 Constructed Doppler map: V_x and V_y are the horizontal component of the gas velocity. The three dots on $V_x = 0$ axis are the center of mass of the companion, the total system, and the compact star, from top to bottom, respectively. The oval shape denotes the companion surface, and the curved line represents a possible ballistic orbit of particles ejected from the L1 point.

Acknowledgements

T.M. was supported by the grant in aid for scientific research of JSPS (13640241). K.O. was supported by the Research Fellowships of the JSPS for Young Scientists. This work was supported by "The 21st Century COE Program of Origin and Evolution of Planetary Systems" in MEXT.

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